

Materials Challenges in Space Exploration

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Abstract: United States civil space program administered by National Aeronautics and Space Administration has a new strategic direction to explore the solar system. This new 'vision for space exploration' encompasses a broad range of human and robotic missions, including the Moon, Mars and destinations beyond. These missions require advanced systems and capabilities that will accelerate the development of many critical technologies, including advanced materials and structural concepts. Specifically, it is planned to develop high-performance materials for vehicle structures, propulsion systems, and space suits; structural concepts for modular assembly for space infrastructure; lightweight deployable and inflatable structures for large space systems and crew habitats; and highly integrated structural systems and advanced thermal management systems for reducing launch mass and volume. This paper will present several materials challenges in advanced space systems—high performance structural and thermal materials, space durable materials, radiation protection materials, and nano-structural materials. Finally, the paper will take a look at the possibility of utilizing materials in situ, i.e., processing and using materials on the surface of the Moon and Mars.

Introduction

On January 14, 2004, President Bush articulated a new vision for Space Exploration in the 21st century. This vision encompasses a broad range of human and robotic missions, including the Moon, Mars and destinations beyond^{1,2}. The fundamental goal of this vision is to advance U.S. scientific, security, and economic interests through a robust space exploration program. In support of this goal the U.S. will pursue four key objectives; these are to:

- Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
- Extend human presence across the solar system starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
- Develop the innovative technologies, knowledge and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security and economic interests.

In August 2004 an interim strategy for Exploration Systems was articulated by Admiral Steidle, Associate Administrator for Exploration Systems Directorate at NASA Headquarters³. The Space Exploration Missions require advanced systems and capabilities that will accelerate the development of many critical technologies, including materials and processing technologies⁴. This paper will present the technology framework, approach to technology development and maturation for space exploration and the materials challenges that must be addressed to realize the goals of Exploration Vision.

Technology Framework for Exploration

Technology development and maturation will be driven by the requirements of various missions envisioned for space exploration. Some key missions and activities of space exploration are listed in Table 1. Requisite technologies must be developed to carry out these missions in a timely but affordable manner. The space technology research, development and maturation follow a process

shown schematically in Figure 1. It is based on technology readiness levels (TRLs). The central concept of TRLs is that the maturation of a particular technology may be characterized in a discipline-

Table 1: Key Elements of Space Exploration Vision¹

1. Return the Space Shuttle to safe flight as soon as practical (2005 target)
2. Use shuttle to complete ISS assembly
3. Retire the Shuttle after the assembly is complete (2010 target)
4. Focus ISS research to support exploration goals; understanding space environment and countermeasures
5. Meet foreign commitments
6. Undertake lunar exploration mission to support sustained human and robotic exploration of Mars and beyond
7. Series of robotic missions to Moon by 2008 to prepare for human exploration
8. Expedition to lunar surface as early as 2015 but no later than 2020
9. Use lunar activities to further science, and test approaches (including lunar resources) for exploration to Mars and beyond
10. Conduct robotic exploration of Mars to prepare for future expedition
11. Conduct robotic exploration across solar system to search for life, understand history of universe, search for resources
12. Conduct advanced telescope searches for habitable environments around other stars
13. Demonstrate power, propulsion, life support capabilities for long duration more distant human and robotic missions
14. Conduct human expeditions to Mars after acquiring adequate knowledge and capability demonstrations
15. Develop a new crew exploration vehicle; flight test before end of decade; human exploration capability by 2014
16. Separate cargo from crew as soon as practical to support ISS
17. Pursue international participation
18. Pursue commercial opportunity for transportation and other services

independent fashion. On the basis of the TRLs, it is possible to frame a typical process/programmatic flow for technology development.^{4,5} The beginnings of technology research are found in fundamental research (TRL 1); these lead, with the conception of a way to apply some new phenomena or analytical insight, to the beginnings of technology (TRL 2). The resulting 'flow' continues through TRL 2 through TRL 5. The technologies are then inserted into a system development program. Hence there are five distinct steps in the strategic knowledge→technology→systems development model:⁴

Step 1: Basic research -- these are programs with the purpose to better understand the world around us. Such research provides the basis for the second step.

Step 2: Supporting advanced space technology research -- this step involves programs that begin with a concept (TRL 2) and lead to the validation of a component and/or breadboard in the laboratory.

Step 3: Focused investment in technology maturation -- this step results in the demonstration of technologies at the system level in a relevant environment.

Step 4: System development projects -- result in new systems with new capabilities.

Step 5: Flight mission project -- this is the final step.

It is important to note in this model for exploration technology that knowledge, technology and missions at each step may be achieved in various organizations within and outside NASA, including other government agencies, universities, private enterprises and international partners.

Cycles of Innovation and Spiral Development:^{4,5} The systems needed to achieve the new U.S vision for Space Exploration will be developed over many years and by diverse organizations. The plan is to develop a focused family of new systems that represent critical 'building block capabilities'

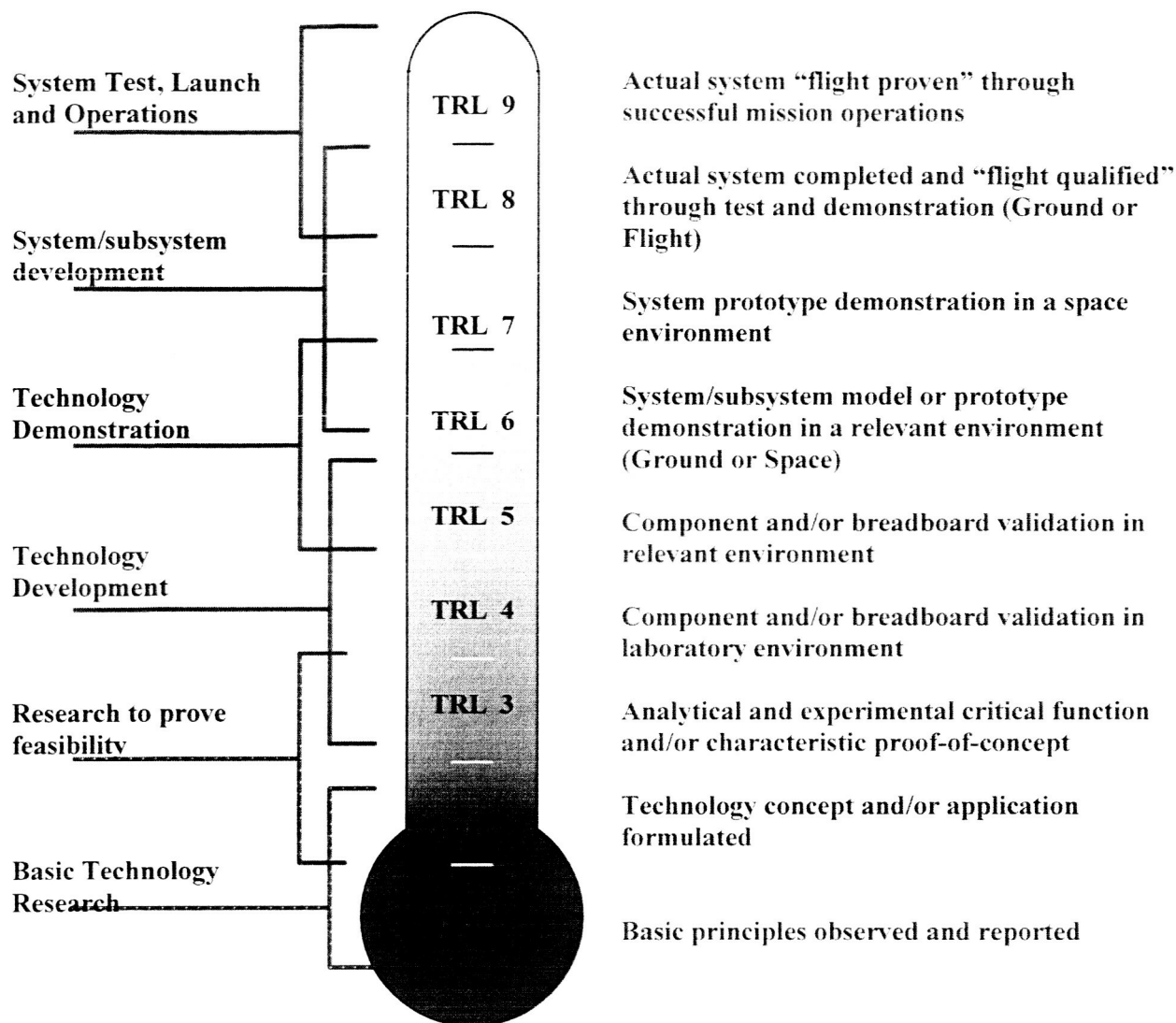


Figure 1: Space Technology Maturation Process: Technology Readiness Levels (TRLs)

for future human and robotic space exploration. These systems will be developed using a 'spiral development' approach. The initial systems will be framed in the context of a broad vision of future missions and systems but without attempting to define in precise detail the specifications or designs for systems that will not enter into full scale systems for years or decades into the future. Instead, long-term program goals and objectives will be established and a range of candidate 'concepts of operations' identified, along with various options for future systems technologies. This development approach will begin with the development of the Crew Exploration Vehicle (Table 1, #15) as a critical first system. Technology development and planning and specific technology projects will be formulated in response to the anticipated course of spiral development. Materials and processing technologies should be developed such that they meet the TRL criteria set forth above in a timely fashion. The technologies should be at TRL 5 or 6 for them to be inserted into a flight program.

Materials and Processes Capabilities for Space Exploration

Materials and processes must be sufficiently mature before they can be used with confidence in building a space system. The level of maturity should be such that materials performance in these

systems is readily predicted and their capabilities are fully understood and utilized in these systems. Figure 2 shows schematically the capability readiness levels (CRLs) for materials/processes⁶. This scheme is analogous to the TRLs for space systems technologies. Materials must be tested and proven in a component/part form in a simulated environment on ground before they can be considered for space applications.

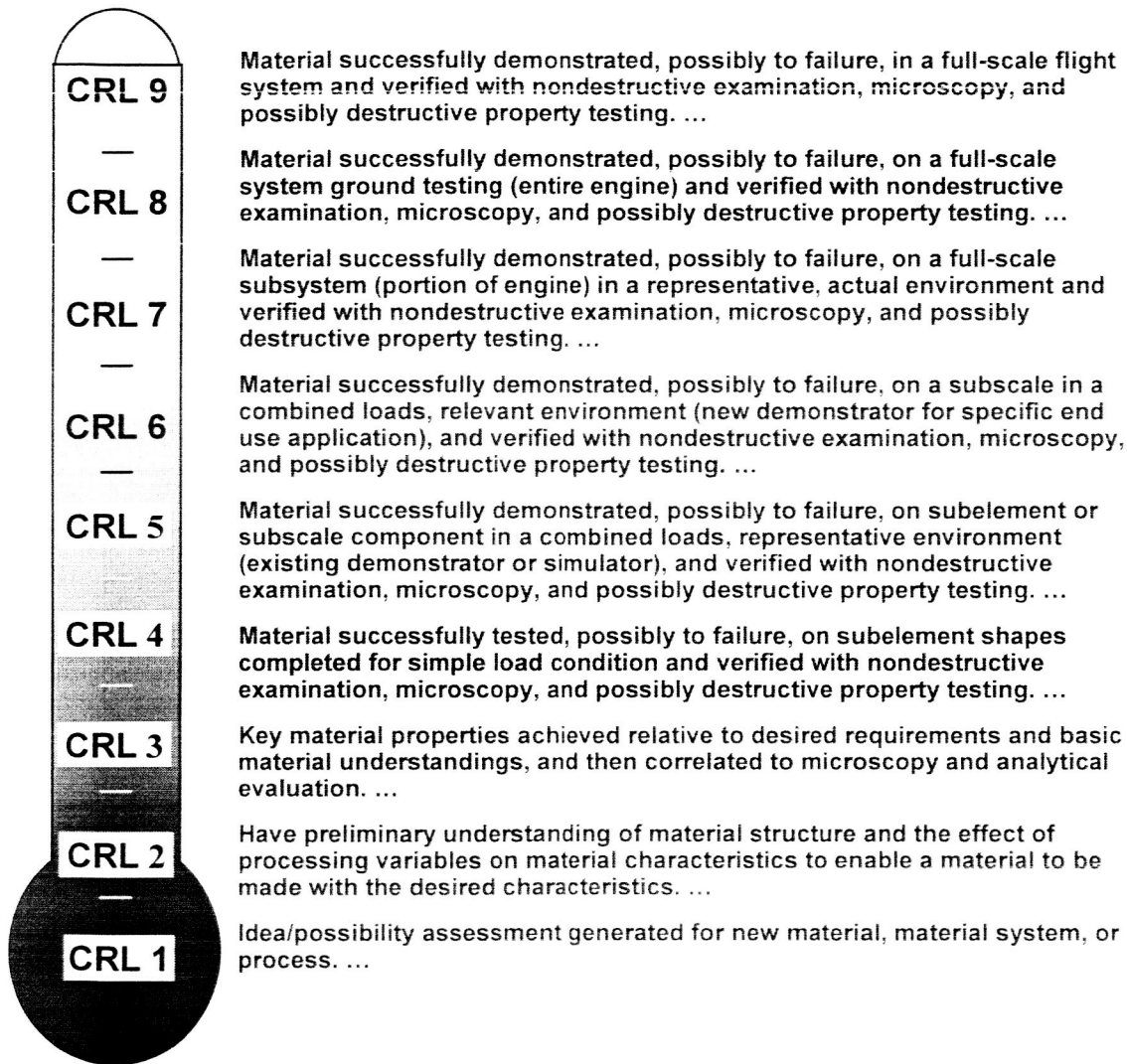


Figure 2: Materials and Processes Maturation Process: Capability Readiness Levels (CRLs)

The task of materials selection and applications in space transportation and space systems is very challenging, since it must take into account many different and often conflicting factors that affect their choice. Materials and processes considered for space applications generally fall into two categories:

1. Existing materials and processes: These materials/processes are already developed and proven either in aerospace or in non-space applications but proposed for use in new space applications
2. New and advanced materials and processes in various stages of development, for aerospace and/or non-aerospace applications, but with limited or no experience.

The first approach is generally lower risk and lower cost, and is almost always preferred. Intuitively it poses less risk to the project. New and advanced materials/processes are considered only if they have

potentially high pay-offs that are worth the extra risk and cost. These materials have to prove themselves before they can be considered as serious candidates for application in a space system. The challenge facing the materials technologists is to reduce the risk of using advanced materials/processes at an affordable cost.

Materials Challenges in Space Exploration

There are several overarching considerations in materials selection for building systems for space exploration:

1. **Materials performance:** The goal here is to minimize the mass of the space systems since the cost per pound of launching payloads is extremely high. At the same time the designer must maintain adequate safety margins, to minimize the risk of mission failure. This requirement drives the designer towards lightweight and high strength metallic alloys, composite materials with very high specific strength and lightweight ceramic materials.
2. **Environmental factors:** Materials must withstand the harsh environment of propulsion systems and the space environment itself. The space environment typically is hard vacuum with galactic cosmic radiation that can be harmful to the materials. Lack of stability of materials in these environments can be life limiting.
3. **Manufacturability:** Any material selected for space systems must be capable of being formed into shapes and joined to build components and subsystems. Special equipment or facilities are often required. The assembled hardware should be capable of being inspected nondestructively.
4. **Affordability:** The materials should be affordable to keep cost under control.
5. **Availability:** The materials should be readily available in order to procure them in sufficient quantities to build flight hardware. Space business is typically a small volume business and often unsteady, and reliable suppliers of key materials may be hard to find.

Materials/processes challenges are presented in the following categories, based on applications:

- Materials for propulsion systems- including chemical and nuclear systems
- Materials for structures and thermal protection systems -- including cryogenic tanks, deployable and inflatable structures
- Materials for space systems—spacecrafts, payloads, environmental control and life support systems for astronauts, including space suits and crew habitats
- Materials for integrated vehicle health monitoring systems
- In-situ materials utilization—on the surface of Moon and Mars

Each category will be discussed in some detail.

Materials Challenges in Propulsion Systems: Two major propulsion systems are considered for space exploration-- chemical and nuclear. Chemical propulsion is commonly used for transportation to and from low earth orbit, and nuclear propulsion systems are proposed for interplanetary travel. Chemical propulsion systems can be solid, liquid or hybrid. Solid propellants are generally used in the boost phase. Liquid propellants are used both for boost and upper stages.

Chemical propulsion systems push materials to their limits because of rapid acceleration, high transients in temperatures and loads. The operating environment is severe, characterized by high temperatures of combustion, cryogenic fuels and oxidizers, and high thermal loading during start up and shut down. High reliability must be maintained in spite of these challenges. Table 2 lists material failure modes in propulsion and vehicle systems and relevant properties. The challenge is to understand the operating environment (thermal, mechanical and environmental) well to make sure that there are sufficient margins on loads and life. Table 3 is a list of properties a material should ideally have—these are goals. Real materials generally lack one or more of these properties and compromises have to be made.

Table 2: Materials Failure Modes and Relevant Properties

<u>Material Failure Mode</u>	<u>Relevant Properties</u>
• Gross yielding	Yield strength (YS), shear YS
• Buckling	Compressive yield strength, modulus of elasticity
• Creep	Creep rate
• Brittle fracture	Impact energy, transition temperature, K_{IC}
• Fatigue, low cycle	Fatigue properties, ductility
• Fatigue, high cycle	Ultimate tensile strength (UTS), fatigue properties
• Contact fatigue	Compressive yield strength (C-YS)
• Fretting	C-YS, Electrochemical potential
• Corrosion-- galvanic	Electrochemical potential
• Stress corrosion cracking	UTS, K_{ISCC} , electrochemical potential
• Hydrogen embrittlement	UTS, chemistry
• Oxidation/combustion	Chemistry
• Wear	Hardness
• Thermal fatigue	Coefficient of thermal expansion, creep rate
• Corrosion fatigue	Fatigue properties, electrochemical potential

Table 3: Ideal Material Properties

<ul style="list-style-type: none"> • High yield and ultimate strengths and ductility • High fracture toughness • High threshold stress intensity (K_{th}) • High fatigue endurance limit • Low crack growth rate (da/dN) • Good capability for a broad range of temperatures • Lightweight • Corrosion resistance • Insensitive to embrittlement (liquid metal, hydrogen, etc.) • Homogenous – less variability in properties • Isotropic – same properties in all directions • Conductivity – high or low depending on application • Radiation (cosmic/nuclear) resistant • Non-degradable with age • Reproducible properties • Manufacturability —machineability, weldability, repairability, inspectability • Affordable
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The earth-to-orbit and upper stage liquid propulsion systems typically use hydrocarbon or hydrogen as fuel. These systems could run either oxygen-rich or hydrogen-rich or combinations thereof. For these engines, materials compatible with high pressure oxygen and/or high pressure hydrogen need to be developed and characterized. Many materials burn readily in oxygen and are unsuitable for application in high pressure oxygen systems. Therefore, they must be tested for resistance to oxidation and promoted combustion to determine their limits of usage in oxygen. Many high strength materials (e.g., Alloy 718) are embrittled in high pressure hydrogen, and therefore, should be well

characterized in hydrogen environment. Only those alloys that are resistant to hydrogen embrittlement should be used. Table 4 lists some common materials used in chemical propulsion systems today. It is essential that the materials are fully characterized in the relevant environment before they are used in design.

Table 4. Common Materials used in Chemical Propulsion Systems

Material Class	Material names	Typical application area
Metallic	Steels	Solid rocket motor case
	Super alloys, e.g., Alloy 718	Power head, turbine housings, pumps, nozzle
	Titanium alloys	Cryogenic pump impellers
	Aluminum alloys	Cryogenic tanks
	Copper alloys	Combustion chamber
Ceramic	C-C, C-SiC	Nozzles
	Silicon Nitride	Cryogenic ball bearings
Polymeric	Polymer Matrix Composite	Nozzles, cryogenic tanks
	Monolithic – viton, teflon	Sealing surfaces, lubrication
High temperature	Refractory metals/alloys	Combustion chamber, sensors
Coatings	Thermal barrier coatings	Combustion chamber, turbine blades

Materials Challenges in Nuclear Propulsion Systems⁷: There are two types of nuclear propulsion systems-- nuclear electric and nuclear thermal. Nuclear electric system uses a radioisotope (plutonium 238) thermoelectric generator for power. A nuclear thermal propulsion system, shown schematically in Figure 3, consists of three components: fusion reactor, heat exchanger and propulsion system. Hydrogen is generally used for cooling and is also the propellant for generating thrust. Astronauts and payloads must be shielded from radiation (gamma rays and neutrons) from the nuclear reactor. Also lightweight heat exchangers (which form the bulk of the total system for RTG electric propulsion) must be built. Low melting metals are often used as cooling media. Important properties are neutron absorption, heat transfer properties, density, viscosity, surface tension and reaction with metallic containment structure. A common problem is reaction with containment materials. Another important consideration is emissivity of the heat exchanger material, since all heat must be dissipated by radiation. The nuclear thermal propulsion engine efficiency is dependent on temperature of operation. Today's technology limits the reactor temperature to about 2800K, but higher temperatures are desirable. This will require higher temperature materials for the reactor, ducts, thrust chamber and nozzle. A carbon-carbon (C-C) nozzle extension is envisioned to improve specific impulse (Isp). Again, lightweight pumps are required to reduce weight. Nuclear radiation might degrade some materials and proper shielding must be used to prevent it. Again, hydrogen embrittlement could be an issue since hot hydrogen flows through the system—turbo pumps, valves and ducts and nozzle. Hydrogen reaction with C-C nozzle extension could degrade its life. Advanced materials and coatings may have to be developed and characterized to meet the mission requirements.

Materials Challenges in Structures and Thermal Protection Systems: Criteria for materials selection for structural applications are very similar to those used for propulsion. Performance, safety margins, cost and availability of materials properties are major considerations. Common structural materials used are alloys of aluminum, titanium, and magnesium, high strength nickel base alloys and steels, and graphite epoxy composite. The composites are attractive because they are lightweight, but they do present problems in joining and repair. Further, composites materials properties are generally more variable than metallic materials, and they are anisotropic, and hence, designing is much harder. They appear to be less tolerant to defects and prone to catastrophic failures. Therefore, improved techniques must be developed both for joining and design to make them more attractive for space applications.

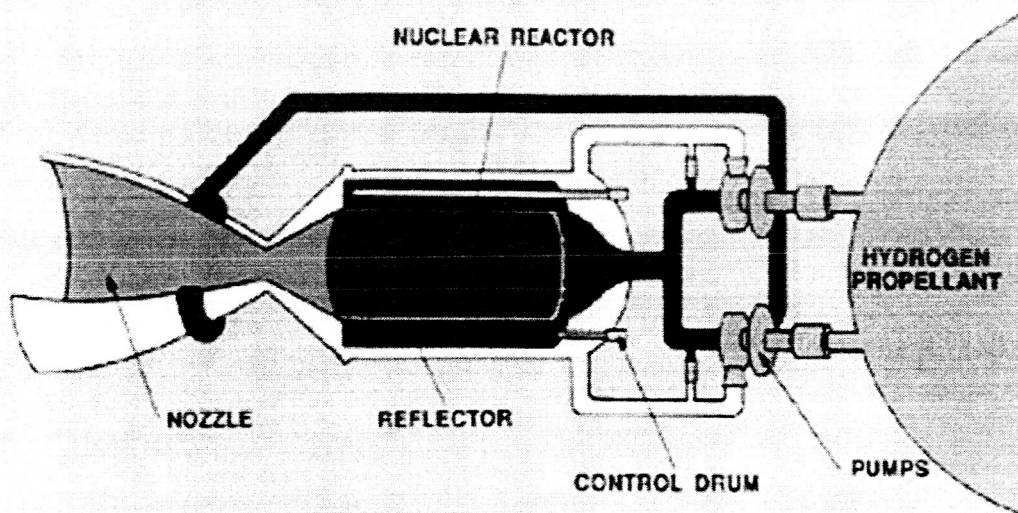


Figure 3. Nuclear Thermal Propulsion Concept

Thermal protection materials are needed for protecting the space craft when entering an atmosphere. Mars has a thin atmosphere which can be used for aero braking. The Spacecraft must withstand the intense heat of reentry to the earth (Examples: Apollo, Soyuz, and Space Shuttle Orbiter). Different types of thermal protection materials are in use, based on silica, alumina and carbon. However, lightweight and higher temperature materials are needed to lower the mass of spacecraft. Similarly, improved lightweight cryogenic insulation materials are needed to minimize boil-off of cryogenic propellants over a long period of storage in space.

Materials Challenges in Space Systems: Space systems include space crafts, space suits and habitats in space or on the Moon. These systems are exposed to the harsh environment of space. The space environment can degrade to the materials in the space systems and adversely affect performance and life⁸. The following environmental factors have been found to have adverse effects on materials:

- Solar ultra-violet flux and solar wind
- Atomic oxygen
- Space vacuum
- Galactic cosmic radiation
- Plasma charging
- Micrometeoroid/space debris
- Spacecraft induced environment
- Contamination

Degrading effects of space environment on different materials are summarized in Table 5.

Spacecraft operating in space vacuum relies on transferring heat to its surroundings by radiating infrared energy. Thermal control coatings are often used to reflect solar energy away and radiate thermal energy. Degradation of these thermal materials may have significant effect on spacecraft thermal control. Contamination of space craft might occur due to out-gassing in space, venting, engine firing, etc. Particulate contamination may be generated by handling during manufacturing, ground processing, launch vibration, moving parts (wear debris), etc. Contamination control can be achieved by material selection, thermal vacuum bake-out, clean room control and space craft design.

Table 5. Space Environmental Effects on Materials

	Atomic Oxygen	UV Radiation	Particulate Radiation	Plasma	Contamination
Metals	Oxides form; silver and osmium eroded	No significant effect	High levels degrade mechanical properties	Charging and arcing may occur on anodized surfaces	Reduces bonding to surfaces
Ceramics	Erosion/mass loss	Some darkening	Compaction may occur	Charging and arcing may occur	Reduces bonding to surfaces
Optics	Oxides form on thin metallic reflector layers	Silica glass darkening	Compaction may occur; Darkening		May cause severe degradation of optical properties
Composites	Binders erode, graphite fibers generally erode at slower rate, fiberglass unaffected	Darkening of fiberglass	High levels affect glass transition temperature, strength	Charging and arcing may occur	Reduces bonding to surfaces; out gassing source
Solar Cells	Attacks silver of electrical connectors	Some darkening of cover sheet	Some degradation of power output	Arcing may occur in high voltage arrays	May affect power output
Polymer Films	With few exceptions, severe erosion occurs	Darkening, embrittlement	Darkening, embrittlement	Charging and arcing may occur	Loss of transmission; out gassing source
Thermal control Coatings	Organic binders erode, leaving pigment particles	Darkening, esp. when contamination is present	Some degradation noted at high levels	Charging and arcing may occur with non-conductive coatings	May cause severe degradation of solar absorptance; out gassing source

Micrometeoroids are naturally occurring particles in space and space debris is human-made. These particles move at very high speeds (8 to 17 Km/sec) and can impact spacecrafts and penetrate space suits (during extra vehicular activity), cause pitting of optics and degrade solar arrays and thermal control materials. Consideration of space environment and contamination early in the program is essential to ensure mission success.

Materials Challenges in Integrated Vehicle Health Monitoring⁹: In space exploration, human rated systems have to be highly reliable. The propulsion systems should be capable of multiple starts. This means that life prediction techniques should be highly reliable and structural health monitoring should be automated such that self-diagnosis and self correction are achieved when communications from ground take too much time. Advanced lightweight sensor materials are required to achieve these goals.

Challenges of In-situ Materials Utilization: To reduce the cost of space exploration it is important to reduce the mass of materials and supplies that must be carried to the Moon or Mars. This is particularly true of human space exploration, in which so far all the consumables were carried from the earth. While this may be satisfactory for low earth orbits (e.g., Space Station) and good for the Moon for a few days, it would prove to be terribly expensive for extended stays on the moon and for trips to Mars. It is highly desirable to use the in-situ materials so that the astronauts can 'live off the land'. Table 6 lists some of the potentially useful materials resources available on the Moon and Mars¹⁰.

Table 6. Potentially Useful In-situ Materials Resources on Moon and Mars

Location	Resource	Potential Use
Moon		
Environment	Vacuum, 1/6 gravity	Materials processing
Atmosphere	none	
Surface	Soil	Radiation shielding
	Melted sintered soil	Construction
	Lava tubes	Thermal shielding
	Metals	Construction
	Non-metals	Solar cells
	Oxygen	Propellant, life support
	Water ice	Propellant, life support
	Hydrogen	Propellant
Mars		
Environment	1/3 gravity, near-vacuum	Materials processing
Atmosphere	Carbon dioxide components	Propellant, life support, plastics
	Nitrogen, Argon	Life support
Surface	Soil	Radiation shielding
	Melted sintered soil	Construction
	Metals	Construction
	Water ice (permafrost)	Propellant, life support

The methods of extracting, purifying and processing materials on the Moon and Mars will be quite different from earth. They have to be fully automated and be ready before the first astronauts land there. Some of the products envisioned are bricks, ceramics and glasses, plastics and metals for use in construction of habitats, power plants and green houses for growing food. Semiconductors such as silicon may be produced for making solar cells for power generation. Any propellants generated in-situ will obviate the need to bring them from the earth. Producing oxygen on the Moon is attractive based on the knowledge gained in the Apollo missions and analyses of the moon rocks and soil. Abundance of carbon dioxide in Mars's atmosphere makes it attractive to produce both rocket fuel and oxidizer on Mars.

Advanced Materials and Processes Technologies for Space Exploration

It is well recognized that success of space exploration depends very heavily on advanced materials. Performance, life and durability of space transportation and in-space systems depend on materials performance to high degree. The materials technology is the principal enabling technology for fulfilling the vision of exploration and discovery. This section attempts to identify some critical materials technologies which must be pursued to ensure successful exploration missions. A summary is given in Table 7.

Materials for Chemical Propulsion Systems: Both earth-to-orbit and in-space transportation depend on chemical propulsion systems. Earth-to-orbit propulsion and transportation technologies are relatively mature but there is a great need for reducing the cost and improving reliability and

Table 7 Advanced Materials and Processes for Space Exploration-- Examples

Application	Materials	Processes
Chemical Propulsion Systems	<ul style="list-style-type: none"> - Hydrogen resistant alloys - Oxygen resistant alloys - High temperature materials for combustion chambers and nozzles - Composites—MMC, CMC (for thrust chamber and nozzle) - Coatings for durability and performance - Nanostructured materials 	<ul style="list-style-type: none"> - Powder metallurgy (PM) processing - Coating techniques-- CVD, PVD, Plasma - Net shape fabrication - Nanotechnology
Nuclear Propulsion and Power Systems	<ul style="list-style-type: none"> - High temperature materials for reactor, pumps, thrust chamber, nozzle - Thermal management materials for heat rejection - Hydrogen resistant materials - Coatings for stability and thermal management 	<ul style="list-style-type: none"> - Welding and joining, including friction stir welding - PM processing - Advanced coatings
Structures and Vehicle Systems	<ul style="list-style-type: none"> - Lightweight, high strength materials for structures and cryotanks—PMC, CMC, Al-Li alloys - Radiation shielding materials - Lightweight TPS materials for heat shield (e.g., aerogels) - Lightweight insulation materials - Smart materials for deployable structures - Nanomaterials - Biomimetic materials 	<ul style="list-style-type: none"> - Friction Stir Welding - Out-of-autoclave curing of PMCs - Nanotechnology - Coating technologies
Space Systems	<ul style="list-style-type: none"> - Lightweight, high strength materials—composites, Al-Be alloys - Materials resistant to space environment - Nanomaterials – polymeric and metallic, - Carbon nanotubes reinforced polymers - Nanostructured coatings 	<ul style="list-style-type: none"> - Composite fabrication - Process modeling - Manufacturing in space - Repair technology in space - Nanomaterials processing - Self-assembly - Coating technologies
Integrated Vehicle Health monitoring (IVHM)	<ul style="list-style-type: none"> - Fiber optics, piezoelectric and other sensor materials - Nanomaterials for sensors - Biomimetic materials—self-diagnosis and self-healing 	<ul style="list-style-type: none"> - Nanotechnology - Processes using lasers
In-situ Materials Utilization	<ul style="list-style-type: none"> - Use of Lunar and Mars regolith - Propellants for chemical propulsion - Silicon for solar cells 	<ul style="list-style-type: none"> - Process development & automation - Rapid prototyping - Laser processing

operability. Cost of manufacturing can be reduced by net shape fabrication techniques and by reducing the number of parts in an engine. Powder metallurgy techniques lend themselves to net shape

fabrication. High temperature materials are needed for thrust chamber to improve life. Nanostructured materials have the potential to improve strength and ductility, and hence, reduce the overall weight.

Materials for Nuclear Propulsion and Power: Nuclear thermal propulsion systems require reliable high temperature nuclear fuels—materials, forms, fabrication techniques and properties. They also need lightweight shielding and thrust chamber materials, long life, lightweight radiation cooled nozzle technologies and long life hydrogen turbo pumps. Radioisotope thermoelectric generators require improved cooling schemes for better heat rejection by radiation—they need to be lightweight and durable in space environment.

Materials for Structures and Vehicle Systems: The thrust here is to develop lightweight structures that are highly reliable and safe for human exploration of space. Aluminum-lithium alloys are promising. Composite materials have the potential to reduce the weight further, especially for tanks for liquid hydrogen. Smart materials can be used to design deployable structures at reduced weight. Lightweight thermal protection systems materials are needed for earth reentry vehicles, and the vehicles that land on Mars.

Materials for In-space Systems: These materials must be resistant to space environment. Radiation shielding materials are necessary to protect the astronauts during extended stays on the Moon or long journey to Mars. New materials may have to be developed if necessary. Lightweight is always important. Advanced materials such as nano-structured materials and smart materials are promising for these applications.

Materials for Integrated Vehicle Health Monitoring (IVHM): Vehicle health monitoring becomes increasingly important as the vehicle moves further away from the earth and the radio signals take a long time to reach the spacecraft. These systems will be highly automated and require many more sensors than in use today, to continuously monitor the conditions of the spacecraft. Sensors have to get much smaller and lighter in order to have more of them. The entire IVHM system has to be light weight. Nanomaterials for sensors appear promising. Biomimetic materials that are self-healing need to be developed.

In-Situ Materials and Processes: There is potential for utilizing materials off the Moon and Mars. However, requisite technologies need to be developed. Knowledge about the environment on the Moon and Mars is growing everyday. This in turn helps to identify more promising technologies that can be and should be developed first. Selection of technologies will depend on the task at hand, which in turn depends on the strategy for the exploration mission. A coherent 'strategy-to-task-to-technology' approach will be used in this spiral development process.

Although there are many advanced materials and processes are in the pipeline (Table 7), exploration mission success may very well depend on breakthrough type technologies, such as nanotechnology. Nanotechnology has the ability to impact every component used in the aerospace systems¹⁰. The research into the fabrication methods, materials, functional devices and modeling will lay the path for future aerospace technologies. Higher strength metallic and polymer composite structures can improve flight performance through lighter weight space systems. Nanostructured coatings provide better protection against the harsh space environment, and wear resistant properties for moving components. A higher operating temperature ability of materials can push the levels of engine performance. Electronic and photonic materials hold the capability to improve flight controls, communications, radiation shielding and self diagnostics. Nanotechnology is very much in its infancy, and the high majority of work is still in the research phase (TRL 1-2). But it has the potential to push levels of performance on all fronts, and enable the development of more efficient and reliable space systems.

Summary

The new vision for space exploration encompasses a broad range of human and robotic missions to the Moon, Mars and beyond. Extended human space travel requires high reliability and high performance systems for propulsion, vehicle structures, thermal and radiation protection, crew habitats and vehicle health monitoring, all of which are dependent on advanced materials. Materials challenges for building such systems include the development of high strength lightweight metallic alloys, ceramics and composite materials, which can withstand the harsh environment of propulsion systems, space radiation and atmospheric reentry. Examples of these materials are given-- hydrogen and oxygen resistant alloys for chemical propulsion, high temperature materials for nuclear propulsion, thermal management materials for thermal protection and heat dissipation, radiation shielding materials to protect astronauts and equipment, coatings to improve properties such as emissivity and resistance to heat and space environment, smart materials for deployable structures, and nanostructured materials for higher strength and ductility. Nanomaterials look promising for sensors used in health monitoring. Advanced processing technologies are required for welding and joining, and net shape fabrication. Nanotechnology looks promising for future spirals. To make Exploration missions more affordable it will be necessary to use of materials on the surface of the Moon and Mars for applications such as construction of habitats, radiation shielding, life support systems and manufacturing of propellants.

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Materials Challenges in Space Exploration



Overview

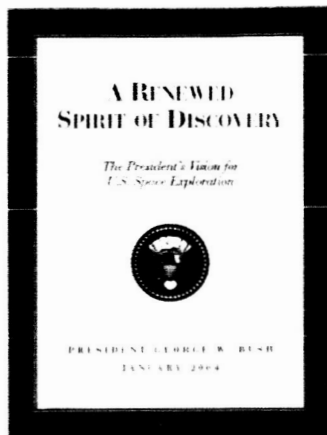
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The New Vision for Space Exploration



- On January 14, 2004, President Bush articulated a new Vision for Space Exploration in the 21st Century
- The Fundamental Goal Of This Vision Is To Advance U.S. Scientific, Security, And Economic Interest Through A Robust Space Exploration Program



- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

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The Key Elements of Space Exploration Vision



1. Return the Shuttle to safe flight as soon as practical, based on CAIB recommendations
2. Use Shuttle to complete ISS assembly
3. Retire the Shuttle after assembly complete (2010 target)
4. Focus ISS research to support exploration goals; understanding space environment and countermeasures
5. Meet foreign commitments
6. Undertake lunar exploration to support sustained human and robotic exploration of Mars and beyond
7. Series of robotic missions to Moon by 2008 to prepare for human exploration
8. Expedition to lunar surface as early as 2015 but no later than 2020
9. Use lunar activities to further science, and test approaches (including lunar resources) for exploration to Mars & beyond
10. Conduct robotic exploration of Mars to prepare for future expedition

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The Key Elements of Space Exploration Vision



11. Conduct robotic exploration across solar system to search for life, understand history of universe, search for resources
12. Conduct advanced telescope searches for habitable environments around other stars
13. Demonstrate power, propulsion, life support capabilities for long duration, more distant human and robotic missions
14. Conduct human expeditions to Mars after acquiring adequate knowledge and capability demonstrations
15. Develop a new Crew Exploration Vehicle; flight test before end of decade; human exploration capability by 2014
16. Separate cargo from crew as soon as practical to support ISS; acquire crew transport to ISS after Shuttle retirement
17. Pursue international participation
18. Pursue commercial opportunity for transportation and other services

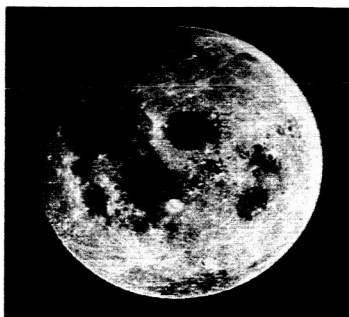
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Missions to the Moon



- 2008: Initial flight test of a Crew Exploration Vehicle (CEV)
- 2008: Launch first lunar robotic orbiter
- 2009-2010: Robotic mission to lunar surface
- 2011 First Unmanned CEV flight
- 2014: First crewed CEV flight
- 2015-2020: First human mission to the Moon



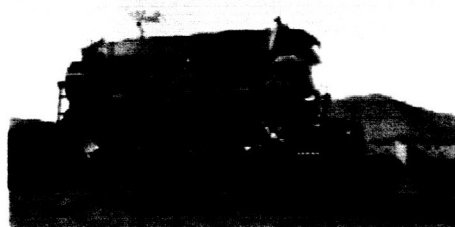
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Preparing for Mars Exploration



- **Moon as a test bed to reduce risk for future human Mars missions**
 - **Technology advancement:** to reduce mission costs and support expanded human exploration
 - **Systems testing and technology test beds:** to develop reliability in harsh environments.
 - **Expanded mission and science surface operations:** to gain experience and develop techniques
 - **Human and machine collaboration:** Machines serve as an extension of human explorers, together achieving more than either can do alone.
 - **Breaking the bonds of dependence on Earth:** (e.g./Life Science/Closed loop life support tests)
 - **Power generation and propulsion:** development and testing
 - **Common investments:** in hardware systems for Moon, Mars and other space objectives



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Technology Framework for Exploration



- Technology development is driven by mission requirements
- Technologies must be developed in a timely but affordable manner
- Technology development and maturation generally occurs in a five-step process:
 - Step 1: Basic research
 - Step 2: Supporting advanced space technology research
 - Step 3: Focused technology maturation
 - Step 4: System development project
 - Step 5: Flight mission project – final step
- Cycles of Innovation and Spiral Development
 - Systems are developed in such a way that they represent 'building block' capabilities for future missions– both human and robotic
 - Technologies will be inserted as they mature into development projects
 - The projects will be developed in a spiral fashion-- first spiral, second spiral, and so on. Each spiral represents a major advancement in technology and capability
 - The first spiral will be the Crew Exploration Vehicle

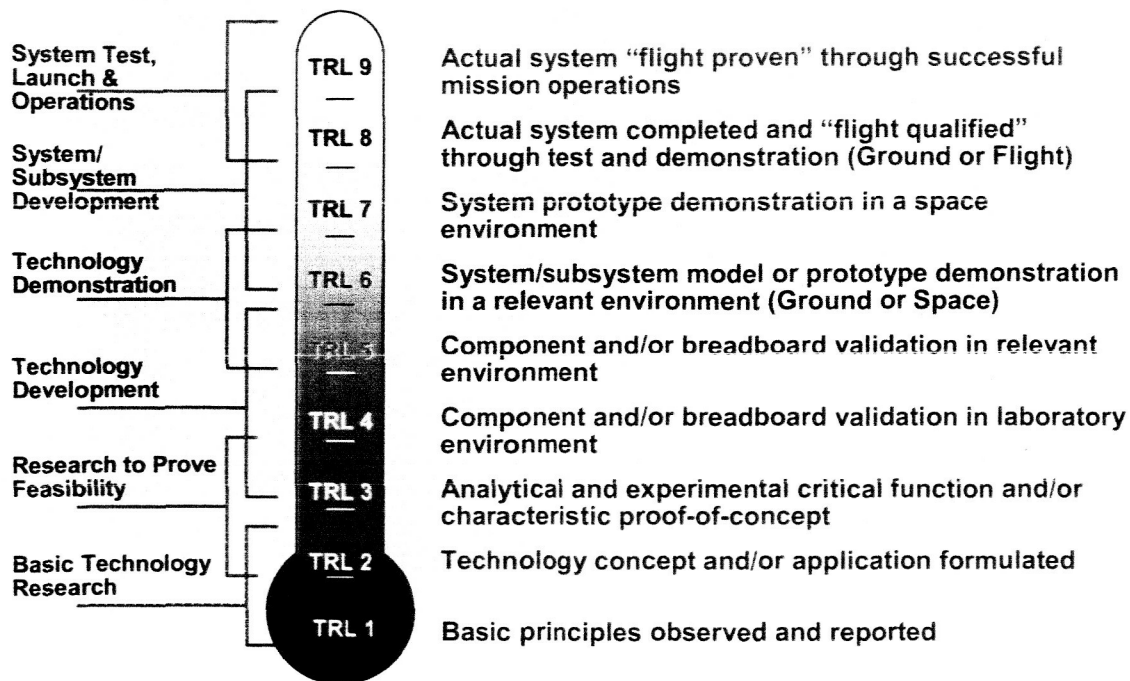
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Technology Maturation Process



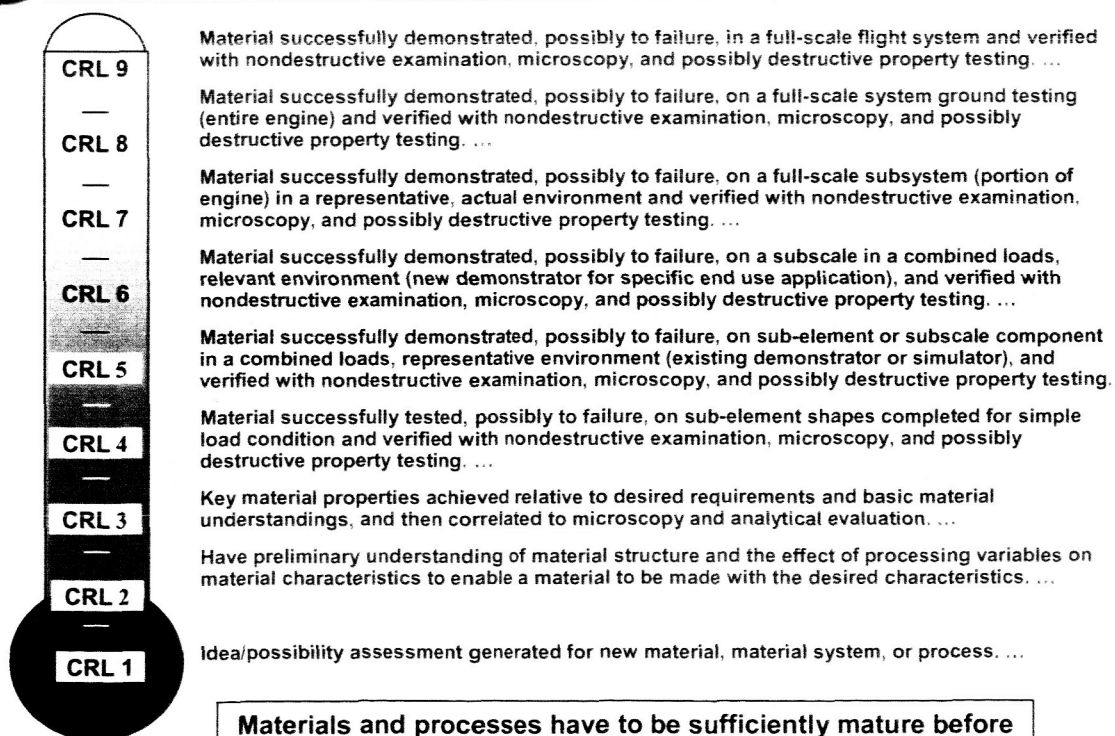
Technology Readiness Levels (TRLs)



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Materials Technologies Maturation Process – Capability Readiness Levels (CRLs)



Materials and processes have to be sufficiently mature before they can be used in system development

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Materials Challenges in Space Exploration



- **Materials and Processes generally fall into two categories**
 - Existing materials and processes— developed and proven
 - New and advanced materials and processes-- in development, not yet proven, but show promise of improved performance or life, lower weight, etc.
- **Use of existing materials presents lower risk and cost**
- **Advanced materials pose higher risk but also present higher pay-offs in terms of performance, weight, life and reliability of space systems**
- **Materials Technologists need to mitigate the risk while preserving the pay-off at an affordable cost**

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Materials Challenges in Space Exploration



- **Materials Selection Criteria**
 - Performance factors: lightweight, high strength, etc.
 - Environmental factors: space environment, radiation effects, elevated temperature
 - Manufacturability
 - Affordability
 - Availability
- **Application Areas**
 - Propulsion Systems – chemical and nuclear
 - Structures and Thermal Protection Systems
 - Space Systems— spacecrafts, space suits, habitats
 - Integrated Vehicle Health Monitoring (IVHM)
 - In-situ Materials Utilization

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Materials Challenges in Space Exploration



Propulsion systems push materials to their limits

<u>Material Failure Mode</u>	<u>Relevant Properties</u>
• Gross yielding	Yield strength (YS), shear YS
• Buckling	Compressive yield strength (C-YS), modulus of elasticity
• Creep	Creep rate
• Brittle fracture	Impact energy, transition temperature, K_{IC}
• Fatigue, low cycle	Fatigue properties, ductility
• Fatigue, high cycle	Ultimate tensile strength (UTS), fatigue properties
• Contact fatigue	Compressive yield strength (C-YS)
• Fretting	C-YS, Electrochemical potential
• Corrosion-- galvanic	Electrochemical potential
• Stress corrosion cracking	UTS, KISCC, electrochemical potential
• Hydrogen embrittlement	UTS, chemistry
• Oxidation/combustion	Chemistry
• Wear	Hardness
• Thermal fatigue	Coefficient of thermal expansion, creep rate
• Corrosion fatigue	Fatigue properties, electrochemical potential

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Materials Challenges in Space Exploration



Ideal Material properties

- High yield and ultimate strengths and ductility
- High fracture toughness
- High threshold stress intensity (K_{th})
- High fatigue endurance limit
- Low crack growth rate (da/dN)
- Good capability for a broad range of temperatures
- Lightweight
- Corrosion resistance
- Insensitive to embrittlement (liquid metal, hydrogen, etc.)
- Homogenous – less variability in properties
- Isotropic – same properties in all directions
- Conductivity – high or low depending on application
- Radiation (cosmic/nuclear) resistance
- Non-degradable with age
- Reproducible properties
- Manufacturability —machineability, weldability, repairability, inspectability
- Affordability

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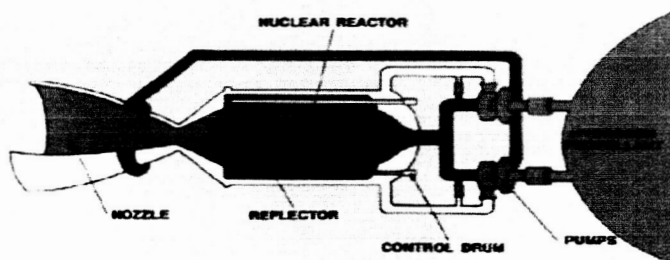


Materials in Nuclear Propulsion Systems



- **Nuclear propulsion Systems**
 - Nuclear electric system uses radio-isotope thermoelectric generator (RTG)
 - Nuclear Thermal Propulsion (NTP) system uses a fusion reactor (see schematic below)
- **Materials Challenges**
 - High temperature materials for fuel and heat exchanger-- $> 2500\text{K}$
 - High temperature materials for ducts, thrust chambers and nozzle
 - Reaction with containment materials
 - Hydrogen reaction & embrittlement
 - Radiation shielding-- neutron absorption
 - Heat exchanger materials – thermal conductivity, emissivity

Schematic of a nuclear thermal propulsion system



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Materials in Structures and Thermal Protection Systems

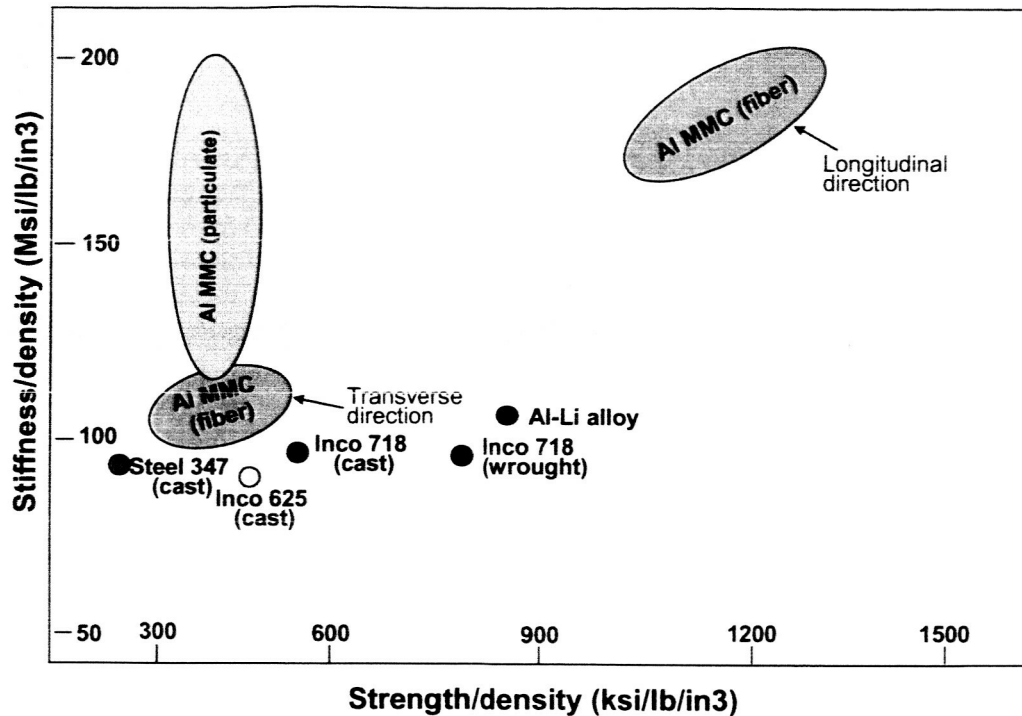


- **Materials Challenges**
 - Availability of materials properties in the application environment
 - Lightweight & high strength
 - High stiffness
 - Manufacturability
 - Repairability
 - Cost
- **Common structural materials– for vehicles and cryogenic tanks**
 - Aluminum and titanium alloys
 - Steels
 - High strength nickel-base alloys
 - Polymer Matrix Composites (PMCs)– carbon-epoxy
 - Metal Matrix Composites (MMCs) – $\text{Al-Al}_2\text{O}_3$
- **Common TPS materials – for reentry and aerobraking**
 - Silica-based
 - Carbon-based: C-C, C-SiC
 - Alumina-based
 - Metallic
- **Cryogenic Insulation Materials – for cryogenic tanks**
 - Foam insulation

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Specific Stiffness vs. Specific Strength



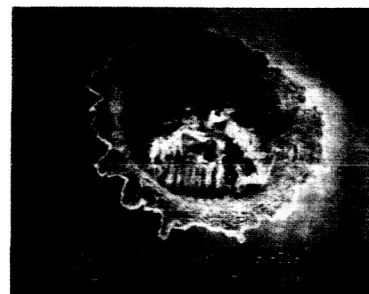
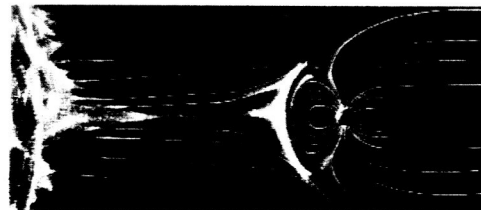
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Materials in Space Systems



- Space Systems include spacecrafts, space suits and habitats in space and on the Moon
- Materials are exposed to harsh environment of space
 - Solar ultra-violet flux
 - Solar wind
 - Atomic oxygen
 - Space vacuum
 - Galactic cosmic radiation
 - Plasma charging
 - Micrometeoroid/space debris
 - Spacecraft induced environment
 - Contamination
- Materials can degrade in space environment
 - Adversely affect spacecraft and its performance



Micrometeoroid debris crater

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Materials in Space Systems



Space Environmental Effects on Materials

	Atomic Oxygen	UV Radiation	Particulate Radiation	Plasma	Contamination
Metals	Oxides form; silver and osmium eroded	No significant effect	High levels degrade mechanical properties	Charging and arcing may occur on anodized surfaces	Reduces bonding to surfaces
Ceramics	Erosion/mass loss	Some darkening	Compaction may occur	Charging and arcing may occur	Reduces bonding to surfaces
Optics	Oxides form on thin metallic reflector layers	Silica glass darkening	Compaction may occur; Darkening		May cause severe degradation of optical properties
Composites	Binders erode, graphite fibers generally erode at slower rate, fiberglass unaffected	Darkening of fiberglass	High levels affect glass transition temperature, strength	Charging and arcing may occur	Reduces bonding to surfaces; outgassing source
Solar Cells	Attacks silver of electrical connectors	Some darkening of cover sheet	Some degradation of power output	Arcing may occur in high voltage arrays	May affect power output
Polymer Films	With few exceptions, severe erosion occurs	Darkening, embrittlement	Darkening, embrittlement	Charging and arcing may occur	Loss of transmission; outgassing source
Thermal Control Coatings	Organic binders erode, leaving pigment particles	Darkening, esp. when contamination is present	Some degradation noted at high levels	Charging and arcing may occur with non-conductive coatings	May cause severe degradation of solar absorptance; outgassing source

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Materials for Integrated Vehicle Health Monitoring (IVHM)



- Human rated systems have to be highly reliable
- Propulsion systems must be reusable -- capable of multiple starts and stops
- Life prediction techniques must be highly reliable
- Structural health monitoring must be automated
 - Monitoring from ground would take too long during interplanetary travel
 - Need for self-diagnosis and self-correction
- Materials challenges: Examples
 - Lightweight sensors embedded in structures-- fiber optics, piezo-electric materials
 - Nano-materials and nano-sensors
 - Biomimetic materials – materials that can heal themselves when damaged

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In-situ Materials Utilization



- Extended stays on the moon or Mars require in-situ resource utilization– to reduce costs
- There are many potentially useful materials on the Moon and Mars– see table below
- Advanced technology must be developed to utilize these resources

Location	Resources	Potential use
Moon		
<ul style="list-style-type: none"> • Environment • Atmosphere • Surface 	Vacuum, 1/6 gravity None Soil Melted sintered soil Lava tubes Metals Non-metals Oxygen Water ice Hydrogen	Materials processing — Radiation shielding Construction Thermal shielding Construction Solar cells Propellant, life support Propellant, life support Propellant
Mars		
<ul style="list-style-type: none"> • Environment • Atmosphere • Surface 	1/3 gravity, near vacuum Carbon dioxide components Nitrogen, argon Soil Melted sintered soil Metals Water ice (permafrost)	Materials processing Propellants, life support, plastics Life support Radiation shielding Construction Construction Propellant, life support

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Advanced Materials Technologies for Space Exploration



- Metallic alloys resistant to hydrogen, oxygen– high specific strength
- High temperatures materials for thrust chambers and nozzles – MMC, CMC
- High temperature materials for reactors and pumps
- Radiation shielding materials for nuclear propulsion
- Materials to resist space environmental degradation in space systems
- Lightweight, high strength materials for structures and cryotanks– PMC, MMC, Al-Li
- Coatings for stability and thermal management in vacuum
- Lightweight TPS materials for heat shield – aerogels
- Lightweight cryogenic insulation materials
- Smart materials for deployable structures
- Nanostructured materials and coatings
- Carbon nanotube reinforced polymers and metals
- Lightweight sensor materials – fiber optics, piezoelectric, temperature sensor
- Biomimetic materials – self diagnosis and self healing
- In-situ materials utilization – use of Lunar and Mars regolith for construction, radiation shielding, propellant production, etc.

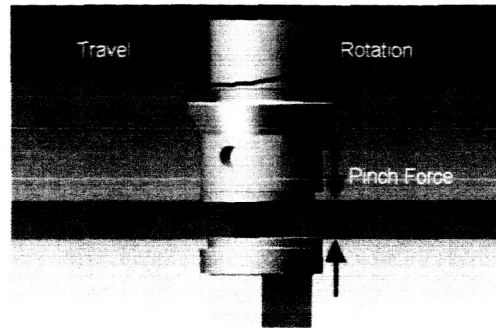
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Advanced Processing Technologies for Space Exploration



- Net shape fabrication -- reduce part count
- Rapid prototyping
- Powder metallurgy processing
- Advanced coating techniques – CVD, PVD, Plasma
- Friction stir welding
- Out-of-autoclave curing of PMCs
- Composite fabrication techniques
- Materials processing in space
- Repair technology in space
- Nanomaterials processing techniques
- Laser processing of materials
- Process modeling
- Process development and automation for processing Lunar and Mars regolith



Self Reacting Friction Stir Welding

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Summary



- The new vision of space exploration encompasses a broad range of human and robotic missions to the Moon, Mars and beyond
- Extended human space travel requires high reliability and high performance systems for propulsion, vehicle structures, thermal and radiation protection, crew habitats and health monitoring
- Advanced materials and processing technologies are necessary to meet the exploration mission requirements
- Materials and processing technologies must be sufficiently mature before they can be inserted into a development program leading to an exploration mission
- Exploration will be more affordable by in-situ utilization of materials on the Moon and Mars

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Summary (Cont'd)



- **Materials challenges for building space systems: Examples**
 - Lightweight, high strength metallic alloys, ceramics and composites
 - High temperature materials for thrust chamber, nozzle, and fusion reactor
 - Radiation shielding and space environment resistant materials
 - Materials for improved thermal management
 - Nanomaterials for sensors, coatings and structures
 - Smart materials for deployable structures
- **Processing challenges: Examples**
 - Net shape fabrication and rapid prototyping
 - Powder metallurgy processing
 - Friction stir welding
 - Composite fabrication -- out of autoclave curing
 - Nanotechnology
 - In-space manufacturing and repair technologies
 - Process modeling and automation

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